The Transmission of Sound Through Sea Water

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DISSERTATION

Presented in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in the Graduate School of the Ohio State University

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BY

LIEUTENANT (J. G.) JERRY HALL SERVICE, B. S., M. S,
U. S. COAST AND GEODETIC SURVEY

The Ohio State University
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PREFACE

Beginning in November, 1923, the author carried out a theoretical and experimental study of the speed of sound in sea water. This work was done under the supervision of Commander N. H. Heck, of the U. S. Coast and Geodetic Survey and of Professor A. D. Cole, of the Department of Physics of the Ohio State University. The results accomplished prior to May, 1924, were considered of such practical importance that they were published later in that year under the joint authorship of Commander Heck and the present author, as U. S. Coast and Geodetic Survey Special Publication No. 108, Velocity of Sound in Sea Water. The author wishes to make acknowledgments for the invaluable help given him in the investigation leading up to the publication of that work by Commander Heck and Mr. D. L. Hazard of the Coast and Geodetic Survey, Dr. George F. McEwen, of the Scripps Institution of Oceanography, Dr. L. H. Adams of the Geophysicial Laboratory of the Carnegie Institution of Washington, and Professor Cole of the Ohio State University.

This dissertation covers the author's work on the Transmission of Sound through Sea Water since June, 1924. The work of the dissertation has been done under the supervision of Professor A. D. Cole, to whom grateful acknowledgment is made for much valuable assistance. Dr. F. C. Blake and Dr. R. F. Earhart, of the Ohio State University, have read the manuscript of the dissertation and made valuable suggestions for its improvement. Dr. Blake has brought to the author's attention, for the first time, Aigner's masterly treatise, "Unterwasserschalltechnik."

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THE TRANSMISSION OF SOUND THROUGH SEA WATER.

BY

LIEUTENANT (J.G.) JERRY H. SERVICE, E.E., Ph.D.

U. S. Coast and Geodetic Survey.

INTRODUCTION. WORK OF HECK AND SERVICE ON SPEED OF SOUND IN SEA WATER.

In 1924 Heck and Service published tables [1] giving the speed of sound in sea water at all depths, temperatures and salinities likely to be encountered in ocean waters. These tables were based upon the independent suggestion of Service in the fall of 1923 that if adequate elasticity and density data were available for sea water the speeds could best be obtained by computation by Newton's equation. Fortunately adequate elasticity data had been made available by the labors of V. W. Ekman [2] and excellent density data had been obtained by Martin Knudsen, Carl Forch, S. P. L. Sörensen and J. P. Jacobsen and published with due acknowledgements by Knudsen in several publications. V. Bjerknes and J. W. Sandström had published [3] tables, based upon the work of Ekman and of Knudsen and his collaboraters, giving the densities and specific volumes of sea water throughout the whole range of physical conditions, and with such small pressure intervals that the elasticities could be obtained by tabular differences. References to Knudsen's publications can be found in that of Bjerknes and Sandström.

At first sight it would seem to be much better to use Ekman's elasticity results directly, together with the density data published by Bjerknes and Sandström, in computing the speeds of sound. But Ekman stated that his elasticity data might be in error by as much as one per cent., which would mean that the speeds of sound computed by this much more laborious, although apparently more accurate, method might be in error by as much as 0.5 of one per cent. It was estimated that in speeds computed by the less laborious method of tabular differences from Bjerknes and Sandström's Tables, errors due to the method of computation would never exceed 0.5 of one per cent., and hence that speeds thus computed

would be of the same order of accuracy as if computed by the apparently more precise method.

Heck and Service used the isothermal elasticities of the water in computing their tables of speed, and included in a separate table corrections to these speeds to take care of the adiabatic conditions that might obtain during transmission; they expressed doubt at the time of publication (1924) as to whether these adiabatic corrections ought to be applied. The writer's experience with echo sounding and radio-acoustic position finding and his consideration of the matter since 1924 have convinced him fully that transmission takes place under adiabatic conditions.

The accuracy of the tables of Heck and Service, when the adiabatic corrections are applied, has been rather well confirmed by experiment and it is considered worth while to reproduce those tables in condensed, skeleton form in this publication. This has been done in Tables 1, 2 and 3, which indicate the manner of variation of the speed of sound in sea water with depth, temperature and salinity, respectively. The solid curves in Fig. 1 are plotted from the values of Heck and Service in Tables 1, 2 and 3. Attention is called to the following facts that are brought out by these tables and curves.

1. Speed increases with temperature approximately 0.2 of one per cent. per degree Centigrade.

2. Speed (at the given depth) increases quite regularly with depth, about 0.2 of one per cent. per 100 fathoms.

TABLE 1.

Variation of Speed of Sound in Sea Water with Depth.

Temperature, 0° C. Salinity, 35 parts per 1000. Depths are in fathoms; speeds, in meters per second.

Depth.	Speed Heck and Service.	Speed British Admiralty.
0	1450	1445
500	1464	1462
1100	1482	1482
1700	1504	1502
2100	1516	1515
2700	1537	1534
3300	1561	1554
3700	1575	1567
4300	1592	1586
4700	1606	1598

TABLE 2.

Variation of Speed of Sound in Sea Water with Temperature.

At the Surface. Salinity, 35 parts per 1000. Temperatures are in degrees Centigrade; speeds, in meters per second.

Temperature	Speed Heck and Service.	Speed British Admiralty.
0	1450	1445
5	1470	1467
10	1490	1487
15	1507	1504
20	1522	1519
22	1529	1524
24	1535	1529
26	1539	1534
28	1542	1539
30	1547	1543

TABLE 3.

Variation of Speed of Sound in Sea Water with Salinity.

At the surface. Temperature, 0° C. Salinities are in parts per 1000; speeds, in meters per second.

Salinity.	Speed Heck and Service.	Speed British Admiralty.
31	1445	1440
32	1446	1442
33	1448	1443
34	1449	1444
35	1450	1445
36	1451	1447
37	1452	1448

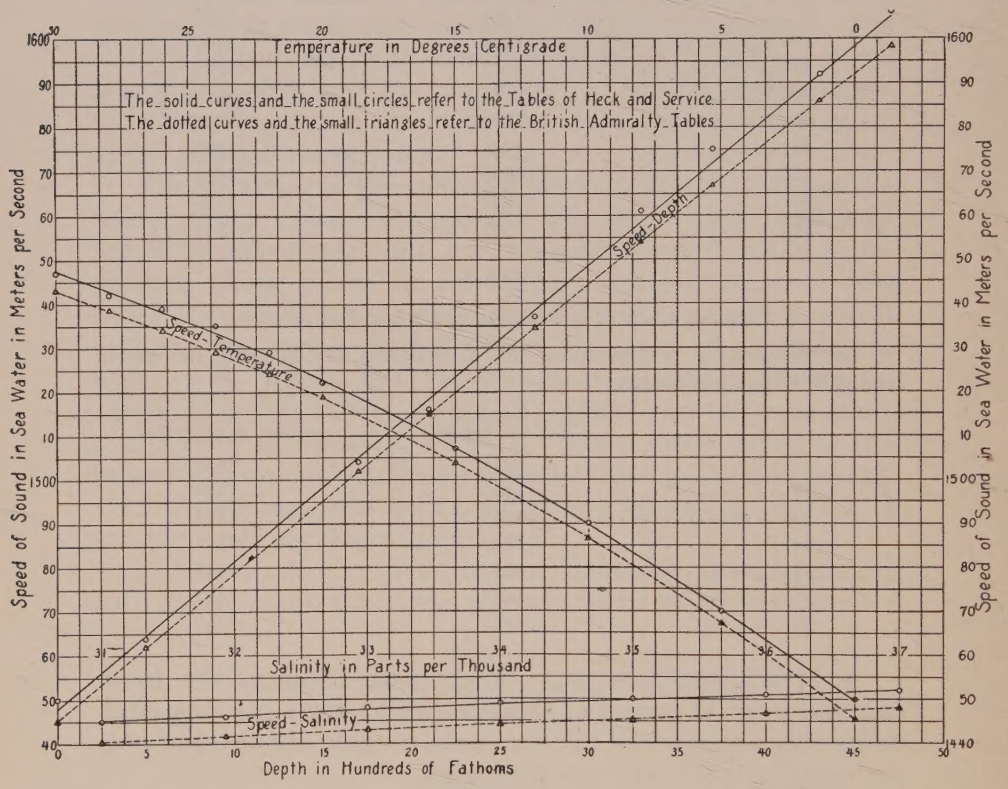
3. Speed increases very slowly with salinity, the total increase from 31 parts per thousand to 37 parts per thousand being only about 0.7 of one per cent., roughly about 0.1 of one per cent. for each part per thousand.

BRITISH ADMIRALTY TABLES OF THE SPEED OF SOUND IN SEA WATER COMPARISON WITH THE TABLES OF HECK AND SERVICE.

In 1927 the British Admiralty [4] published an excellent and very complete set of tables of the speed of sound in water, which were computed and prepared by Mr. D. J. Mathews on the basis of Newton's equation from the same elasticity and density data as were used by Heck and Service. Mr. Mathews, however, used Ekman's elasticity data directly,

thus avoiding small errors due to the method of computation to which the tables of Heck and Service are liable. Tables 1, 2 and 3 and Fig. 1, which show a fair selection of corresponding values of Heck and Service and of the British Admiralty, indicate the order of magnitude of those small errors. The

FIG. 1.


Temperature in Degrees Centigrade
The solid curves and the small circles refer to the Tables of Heck and Service.
The dotted curves and the small triangles refer to the British Admiralty Tables.
Speed - Depth
Speed - Temperature
Speed - Salinity
Salinity in Parts per Thousand
Depth in Hundreds of Fathoms
Speed of Sound in Sea Water in Meters per Second

British Admiralty tables are free from tabular irregularities, as shown by the dotted curves of Fig. 1, and as might be expected. The maximum discrepancy between the two sets of tables is about 8 meters per second, or about 0.5 of one per cent. The British Admiralty speeds are systematically lower than those of Heck and Service by about 4 meters, or about one-fourth of one per cent. due simply to the difference in the methods of computation. It must be remembered that these

differences are of the same order as the probable errors in the speeds due to the probable errors of the very excellent experimental data of Ekman.

From the standpoint of convenience for echo sounding work, where the soundings are taken in fathoms the tables of Heck and Service including the application of the adiabatic correction involve less computation in their use than do those of the British Admiralty. For echo sounding work where the soundings are taken in meters and for radio-acoustic ranging where distances are required in meters, the British Admiralty tables involve very little, if any, more computation than do the tables of Heck and Service.

TABLE 4.

Comparison of the Results of Precise Measurements of the Speed of Sound in Sea Water with the Corresponding Values in the Tables of Heck and Service and of the British Admiralty, Respectively.

All measurements were made in comparatively shallow water.

Experimenter.	Temperature deg. Cent.	Salinity parts per 1000.	Measured Speed m/sec.	Speed Heck and Service m/sec.	Speed British Admiralty m/sec.
Stephenson [6]	−0.3	33.5	1,453	1,449	1,442.2
Marti [7]	15	32.3	1,504.15	1,503	1,500.9
Wood, Browne, Cochrane[8]	6	35	1,474.0	1,474	1,472.0
Wood, Browne, Cochrane[8]	7	35	1,477.3	1,478	1,476.1
Wood, Browne, Cochrane[8]	16.95	35	1,510.4	1,514	1,510.4
Eckhardt [13] See Note	13	33.5	1,492.3	1,498	1,495.5

Note.—The author took part in Eckhardt's measurements of speed and knows his measurements to have been of very great precision indeed. The distance was about 100,000 meters. Unfortunately, however, inadequate temperature observations were made over the range between bombs and hydrophones, so that his temperature as given above is perhaps a little higher than the true mean value between surface and bottom over the whole range.

The British Admiralty has rendered a great service to navigators by its Table 1 in which are given sound speeds to be used in echo soundings in various ocean areas. The navigator is not in a position either to measure or to search out in the literature the temperature and salinity conditions obtaining at various depths in the regions where he may wish to take echo soundings. Tables should be prepared for his

use giving him the correct speed of sound to use for a sounding of approximately a given depth in a given ocean area. This the British Admiralty has done in its Table 1. Heck and Service have published [5] convenient data of this kind for the whole Pacific Ocean.

A further comparative test of the tables of Heck and Service with those of the British Admiralty can be made by checking both against the results of precise measurements of the speed of sound in sea water under known conditions of temperature and salinity. Such a test is applied in Table 4.

MEASUREMENTS OF THE SPEED OF SOUND IN SEA WATER BY THE GERMAN SURVEY AND RESEARCH SHIP METEOR.

The German Atlantic Expedition has, upon some 250 stations occupied by the Survey and Research Ship *Meteor*, obtained simultaneous pressure soundings, echo soundings and serial temperature and salinity measurements. These 250 stations are distributed from the Antarctic Ocean through the tropics into the North Atlantic Ocean. Since the simultaneous pressure and echo soundings give the depth and the time of return of the echo, together they constitute a measurement of the speed of sound in sea water corresponding to known conditions of pressure, temperature and salinity. It is to be expected that when this wealth of material has been worked up an important contribution will be made to the knowledge of the speed of sound in sea water.[9]

TESTS OF THE TABLES OF HECK AND SERVICE BY PIANO WIRE AND ECHO SOUNDINGS BY THE U. S. COAST AND GEODETIC SURVEY.

Heck and Service checked [1] their tables against simultaneous piano wire and echo soundings on 44 stations occupied by the Survey Ship *Guide* on an oceanographic cruise. The temperature and salinity conditions on these 44 stations were fairly well known by means of serial temperature and salinity observations made by the *Guide*. They found an average percentage difference between the speeds from their tables, without the adiabatic corrections, and the measured speeds, of 0.2 of one per cent. The author has repeated this comparison, applying the adiabatic corrections, and has found that the effect of the corrections is to reduce the average percentage difference between the measured speeds and those from the

tables to *zero*, although as before there were individual discrepancies as great as 3.4 per cent. between measured and computed speeds.

Lieutenant E. W. Eickelberg, U. S. Coast and Geodetic Survey, in connection with the test of the fathometer that he installed on board the Survey Ship *Discoverer*, made a rather large number of simultaneous piano wire and echo soundings in the Pacific Ocean near the Hawaiian Islands. A considerable number of serial temperature observations were taken; also the salinity was fairly well known. He found that when he computed his echo soundings by speeds from the tables of Heck and Service, the echo sounding practically never differed from the piano wire sounding by more than one per cent., which included errors of observation in both soundings, errors of observation of temperature and the error of slope of the echo sounding.

DETERMINATION OF SOUND SPEEDS FOR ECHO SOUNDING IN THE U. S. COAST AND GEODETIC SURVEY.

Instructions for echo sounding in the U. S. Coast and Geodetic Survey require the hydrographer to take serial temperatures in the area to be surveyed, with the vertical interval such that the change of temperature between successive layers shall not exceed one degree Centigrade and with spacing of serial temperatures over the area such that the weighted mean temperatures from adjacent stations shall not differ by more than one degree Centigrade. These temperature observations are checked from time to time during a working season to detect any seasonal change should one occur that is of practical importance.

The author [10] has worked up simple procedure for the measurement of salinity of sea water: (1) by hydrometer; (2) by titration with silver nitrate with potassium chromate as indicator; and (3) by the dipping refractometer. Any of these methods can be used on board a vessel under way to give salinity, even in inexperienced hands, with an uncertainty not greater than 2 or 3 in the third significant figure. The hydrographer is required to make salinity measurements at such vertical intervals and with such spacing over the area that he will be sure of the second figure of salinity in any layer in any part of the area.

By means of the temperature and salinity data so obtained and the speed of sound tables of Heck and Service, the hydrographer can easily work up the values of speed of sound in convenient layers in the various sections of the area. The speed to be used in sounding to a given depth in a given section of the area is then the weighted mean of the layer speeds down to that depth.

DETERMINATION OF SOUND SPEEDS FOR RADIO-ACOUSTIC POSITION FINDING IN THE U. S. COAST AND GEODETIC SURVEY.

In the Coast and Geodetic Survey up to the present time, sound speeds for use in radio-acoustic position finding [11] have been determined almost exclusively by direct measurement. The ship, while within range of visibility of shore objects, fires a bomb in the water alongside and at the same time fixes its position by means of angles between shore objects measured on board the ship with sextants. The radio-acoustic apparatus measures the time of sound travel from the ship to the hydrophone at each of the shore stations. The positions of these hydrophones are plotted on the hydrographic sheet so that as soon as the ship's position has been plotted, the distance from the ship to each hydrophone can be scaled off. Thus two distances (usually only two stations are used) with the corresponding times of sound travel are obtained, which give two values of the speed of sound. It has been the practice of the Survey Ships in the past to use the mean of a large number of values of speed so measured during the season, for reducing and plotting all the radio-acoustic positions obtained by that ship during that season.

Since areas in which the ship's positions are fixed by the radio-acoustic method are usually sounded by the echo method, and since the temperature and salinity conditions in those areas would be therefore already determined as explained in the preceding section, it is the opinion of the writer that sound speeds for radio-acoustic position finding would be more accurately obtained from the tables of Heck and Service or of the British Admiralty rather than by direct measurement. The data presented in the next section, which is impartial, gives evidence that the probable errors of speeds taken from the tables would not be great, certainly no greater than

the errors inherent in the present practice. Furthermore, temperature and salinity conditions can be determined as far offshore as radio-acoustic positions are carried, while direct measurements of speed can be effected only within range of visibility of shore objects where generally the radio-acoustic method *will not be used;* the average physical conditions of the water over the ranges where the method *is used* will probably not be the same as those over the ranges where the speeds are measured.

TRANSMISSION OF SOUND IN RADIO-ACOUSTIC POSITION FINDING.

Early in 1925 the author had occasion to study speeds of sound measured as explained in the preceding section in 1924 by the *Guide* in the vicinity of Cape Blanco, Oregon, and to study the measured speeds in connection with temperatures measured by the *Guide* in the same area at about the same time for the Scripps Institution of Oceanography. The mean temperature over the straight line paths between bombs and hydrophones during the month of July was 11° C.; the salinity was 33 parts per thousand, very nearly. The mean measured value of speed was 1,473 meters per second. For the given conditions the tables of Heck and Service give a speed of 1,492 meters per second; *the discrepancy between this value and the measured value is considerably in excess of the combined possible errors of measured speed, measured temperature and the tables.* On the other hand, the *mean temperature between surface and bottom* over the area in which measurements of speed were made during July was 7° C.; the salinity was 33. The tables give for these conditions a speed of 1,475 meters per second, *which is in very fair agreement with the measured value, 1,473.*

The mean measured value of speed in October was 1,493 meters per second. The mean temperature from surface to bottom was 11° C.; the mean salinity was 33. For these conditions the tables give a speed of 1,491 meters per second, which also agrees very fairly with the measured value. Unfortunately no serial temperature observations were made during August or September.

This correspondence between speed of sound directly measured for horizontal transmission and the mean effective pressure,

temperature and salinity between surface and bottom over the range between bomb and hydrophone was independently discovered by the writer in the spring of 1925 and was announced to the Commanding Officer of the *Pioneer* through the Commanding Officer of the *Guide* in a letter written at San Pedro, California, on March 7, 1925.

The author at that time proposed (in the above-mentioned letter) the following hypothesis as to the mechanism of horizontal sound transmission, with which hypothesis, it is well to state frankly, many of his superior officers and associates disagree: that the sound energy from the bomb makes its way to the hydrophone principally by multiple reflections between surface and bottom*; whatever may precede it, the peak value of power received at the hydrophone, the peak that sets into operation the automatic transmitter [11] of the radio-acoustic apparatus, comes from bomb to hydrophone by way of all the horizontal layers of water between bomb and hydrophone; since the loss of energy by reflection increases as the incident and reflected wave fronts approach parallelism with the reflecting surface, the effective sound energy is propagated by very oblique reflections, so that the total length of path is not appreciably in excess of the distance measured along the surface from bomb to hydrophone; if the water between bomb and hydrophone is deep, fewer reflections and less loss of energy by reflection will occur than if the water is shoal, that is, a given quantity of sound energy released by a sound source can be transmitted practically to greater distances in deep water than in shoal water. In other words, the surface and bottom form a great two-walled speaking tube; as in any speaking tube if the walls are too close together so that the tube has too small a cross sectional area transmission will not be efficient. Upon this hypothesis it would be expected that sound could be transmitted to greater distances when the surface of the sea is smooth, other conditions being equal, than in rough weather; such seems to be the case. Likewise, the distance to which sound could be transmitted would depend upon the material and configuration of the bottom; the

* In shoal water, such as off North Carolina and Florida, evidently this must be the case because the straight line between bomb and hydrophone passes below the surface by a distance exceeding the depth of water.

author is not prepared to present evidence of the effect of the bottom material upon the transmission of sound in radio-acoustic position finding, but in the following are described two cases where it is believed that the failure of the radio-acoustic method can be attributed to a peculiar configuration of the bottom.

Professor Cole has, in this connection, reminded the writer of some early measurements of the speed of sound in air that were carried out in the water mains of Paris, where the speed was found to be a function of the diameter of the pipe, being greater for the larger pipes. This work was done by Regnault in 1862–63.[17] Regnault found also that the decrease of intensity with distance was greater, the less the diameter of the pipe. The writer would suggest that the two effects are probably closely related, for in sea water, at least, the speed increases with intensity, as pointed out in the last section of this dissertation. How could either effect be explained if transmission by multiple reflections between the walls be not assumed?

Dr. Earhart has reminded the author that the case of multiple reflections between surface and bottom is not quite analogous to the experiments of Regnault, because when the sound is reflected from the under surface of the water a change of phase of 180° occurs, where in the multiple reflections between the inner walls of the pipe no phase change occurs.

It had been found in the summer of 1924 that sound could not be transmitted appreciably across a submerged bank, steep on the seaward (bomb) side, located a few miles northwest from Cape Blanco, Oregon, although the crest of this bank was far below the straight line paths between bombs and hydrophones. This phenomenon was cited by the writer in his letter above mentioned in support of his hypothesis. For by his hypothesis a great part of the energy from the bomb would be reflected from the seaward side of the bank at nearly normal incidence with resulting great loss by reflection; in fact some of the energy would be reflected backward and wholly lost.

In like manner, it was found that no appreciable sound energy could be transmitted across Cortez Bank or Tanner Bank, off the coast of southern California, in the work of the *Guide* in the winter and spring of 1925, although the banks did

not intercept the straight line paths between bombs and hydrophones. These banks are extremely steep on the sides away from San Clemente Island, where the hydrophones were located.

Here Dr. Earhart suggests that if the theory of transmission proposed is correct and the effect on transmission from deep water to a bank is a fact, then the attenuation would be different according to whether the sound travels across the bank toward the shore or away from shore, and that this difference of attenuation might be capable of experimental verification.

In 1926 the *Guide* and *Pioneer*, working in adjacent areas north and south, respectively, of the mouth of the Columbia River, made a large number of measurements of the speed of sound in sea water for use in plotting the season's radio-acoustic positions. Unfortunately, not enough temperature and salinity data is available for the *Pioneer's* area to make her measurements of value for this study. The same is true of the *Guide's* area so far as measurements made in connection with her northern station (Westport, Washington) are concerned; but the area involved in measurements made in connection with her southern station at North Head, although the temperature and salinity data even here are inadequate, is fairly well represented by well-distributed temperature and salinity measurements made by the *Guide*. These serial observations yield a mean effective temperature from surface to bottom over the area covered by the measurements, of 6° C., and a corresponding salinity of 33 parts per thousand. The tables of Heck and Service give for these conditions a speed of 1,471 meters per second. The mean of the measured speeds was 1,469 meters per second. This very fair agreement is cited as further evidence in favor of the author's hypothesis as to the manner of transmission of the peak of power from bomb to hydrophone (giving due consideration to the fact that the temperature and salinity data are not adequate), because the temperature and salinity along the straight line path were approximately 13° C. and 33 parts per thousand, respectively, and the tables of Heck and Service for these conditions give a speed of 1,498 meters per second. The great discrepancy between this latter value and the mean measured value is far in

excess of the combined probable errors of the speed and temperature measurements and the speed tables.

It is evident that on the author's hypothesis the rate of decrease of intensity with increasing distance from the source will be less, and the range of a given hydrophone will be greater than on the assumption that the hydrophone is actuated solely by sound energy that follows the straight line path; for the intensity (on the author's hypothesis) will be more nearly proportional to the inverse first power than to the inverse square of distance.

The author wishes to state that he has advanced the above explanation merely as an hypothesis that seems consistent with such experimental data as are at hand. It does not appear to be inconsistent with any physical principles. It seems probable to the author, who has listened during several years to echoes from the ocean bottom, and who realizes that the bottom is a better reflector of sound, even at perpendicular incidence, than is generally supposed.

At the same time, the important thing in the preceding part of this section is not this hypothesis, but the experimentally verified correspondence of the speed of sound with the mean physical conditions between surface and bottom, and the effect of submerged banks upon the horizontal transmission of sound energy. The hypothesis may or may not be correct; the author will be ready to discard it when he is convinced that it is untenable, or when a more probable explanation comes to his attention. But the correspondence between speed and mean conditions has at least a considerable mass of experimental data in its support.

If the above hypothesis has no other virtue, it has justified its existence by the wealth of constructive criticism that it has evoked from the author's professors at the Ohio State University. Professor Cole has advanced an alternative explanation; Dr. F. C. Blake has introduced the author to Aigner's excellent treatise "Unterwasserschalltechnik," and Aigner verifies Professor Cole's explanation; Dr. R. F. Earhart has advanced a second alternative explanation. It is quite possible that after further reflection and calculation based upon these new ideas, the author may reject his multiple

reflection hypothesis altogether or at least modify it very radically.

Professor Cole has suggested independently that although the usual temperature gradient has the effect of refracting the direction of propagation downward (because the speed is greater in warm water than in cold), nevertheless in deep water the increase of speed with increasing pressure may well more than neutralize the temperature effect, so that the sound energy may follow a path through nearly all the layers between surface and bottom and yet be deflected upward toward the surface without reaching the bottom at all.

Aigner [20] has proved by calculation that the above explanation made independently by Professor Cole is feasible. His German is so excellent that the author is unwilling to spoil it by translation and therefore quotes it verbatim.

" . . . ist letztere (die Kompressibilitätskoeffizientenänderung) bei Wasser von 0° C. bei einer Druckzunahme auf 200 Atmosphären (corresponding to an increase of depth of about 1000 fathoms) ebenso groß wie bei einer Temperatursteigerung von 0° auf 20° C. Da aber diese beiden Effekte hinsichtlich der Schallgeschwindigkeitsänderungen einander entgegenarbeiten, falls die Temperaturschichtung anotherm ist, so folgt daraus, daß in diesem Falle bei einer durchschnittlichen Wassertiefe von 2 km eine Kompensation eintritt, somit auch im Sommer der schädliche Temperatureinfluß nicht zur Geltung kommt. In noch tieferen Gewässern findet bei gleicher Temperatur-Differenz un -Richtung sogar eine Ablenkung der Schallstrahlen gegen die Wasseroberfläche zu statt. Es ist daher zu erwarten, daß in Gewässern, in denen der schädliche Temperatureinfluß durch eine entsprechende Wassertiefe mindestens kompensiert wird, Reichweiten von einigen tausend Kilometern mit unverhältnismäßig kleinem Strahlungsleistungen zu erziehlen sind. Es entbehrt dabei die Ueberlegung nicht eines besonderen Reizes, daß eine Depesche über eine Strecke von 1,500 km ca. eine Viertelstunde benötigt, bis sich die akustische Energie von der Sendestation durch das wogende Weltmeer zur Empfangsstation durchgearbeitet hat. Leider liegen diesbezüglich bis heute keinerlei systematische Messungen im tiefen Ozean vor."

The author would suggest that when the source is below the region of high temperature gradient, as it can well be in radio-acoustic position finding, the effective range will be greater, according to Professor Cole's hypothesis as confirmed by Aigner, because then no downward refraction but rather upward refraction will occur in the early part of the travel.

Dr. R. F. Earhart rejects the author's multiple reflection hypothesis entirely. He makes an alternative suggestion as to the mechanism of transmission that has much to commend it, and which it seems well to include here. His suggestion is that as the wave advances the mechanical drag of the bottom upon the longitudinal vibrations of the particles "tips over" the waves much as water waves are tipped over and broken when they advance into the shoal water near the beach. As the waves are tipped over they are caused to strike the bottom and are absorbed, the effect being much the same as when sound is propagated against the wind in air. The effect will be relatively greater in shoal water than in deep, so that the effective range of a given source will be less in shoal water than in deep water, as is in accord with experience. The speed of propagation would be determined, so he states, by the mean effective physical conditions between surface and bottom, which is also in accord with experience.

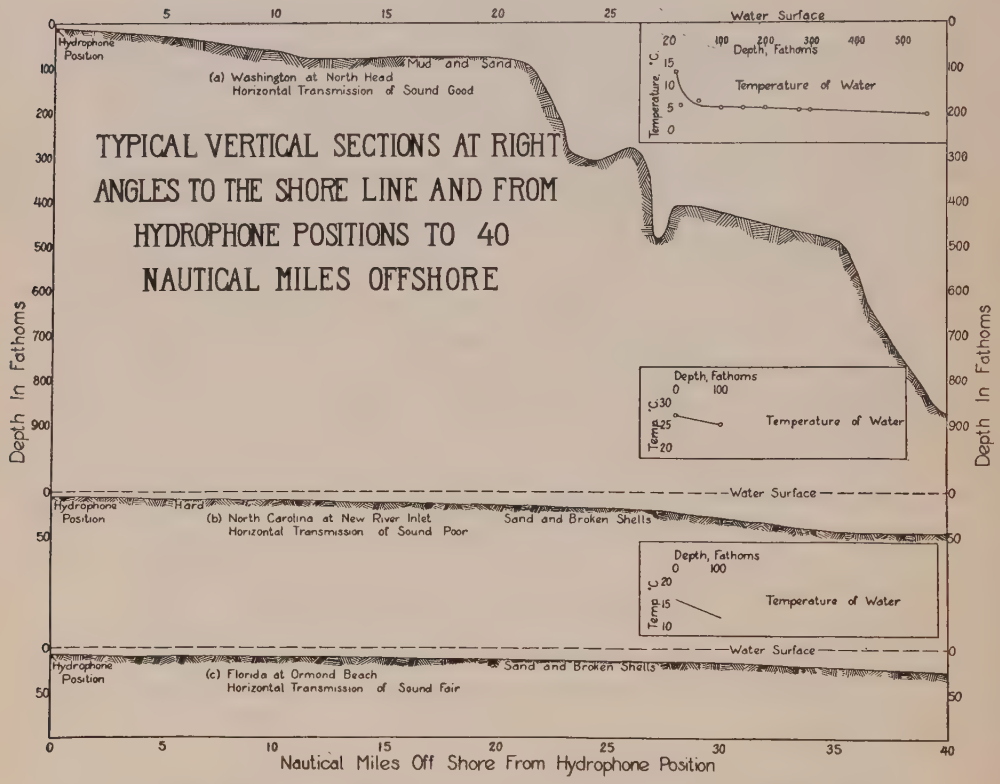
EXPERIENCE WITH RADIO-ACOUSTIC POSITION FINDING [11] IN VARIOUS REGIONS.

(*a*) In the Waters off Washington and Oregon.

In July, 1925, the writer planted hydrophones and laid hydrophone cables for the *Guide* at Port Orford, Hunter's Cove and Brookings, Oregon. These were the first shielded hydrophones used by the Coast and Geodetic Survey. The shielding was done under the direction of the writer and grew out of his study of the work of Brillié, as discussed in a later section of this dissertation. During the month of August, 1925, the *Guide* made a test run, steaming directly offshore from the Hunter's Cove station and firing a bomb in the water near the ship about once every half hour. A type of bomb designed by the writer, consisting of a hollow cast iron sphere of five inches inside diameter and one-half inch wall thickness, packed with loose TNT in which was imbedded a fulminate detonator with waterproof fuse, was found to be

most effective. Positions were obtained consistently with these bombs from the Port Orford and Hunter's Cove stations until the ship was more than two hundred (200) statute miles offshore and approximately that distance from each of the

FIG. 2.


TYPICAL VERTICAL SECTIONS AT RIGHT ANGLES TO THE SHORE LINE AND FROM HYDROPHONE POSITIONS TO 40 NAUTICAL MILES OFFSHORE
Water Surface
Hydrophone Position
(a) Washington at North Head
Horizontal Transmission of Sound Good
Mud and Sand
Depth, Fathoms
Temperature, °C.
Temperature of Water
Depth In Fathoms
(b) North Carolina at New River Inlet
Horizontal Transmission of Sound Poor
Hard
Sand and Broken Shells
(c) Florida at Ormond Beach
Horizontal Transmission of Sound Fair
Nautical Miles Off Shore From Hydrophone Position

two stations. At that distance the ship got out of range of the shore station radio transmitters; the limit of the range of sound transmission had not yet been reached. For some reason not well understood no appreciable energy from the bombs reached the hydrophone at Brookings. This remarkably successful run proved the practicability of the radio-acoustic method of controlling the momevents of a survey vessel on survey duty, at least in the waters off the Oregon and Washington coasts, and marked the beginning of the successful practical use of the method in those waters.

As an example of the practical use of radio-acoustic position finding in the waters off the coasts of Washington and Oregon, it may be stated that in 1926 the *Guide* surveyed the area between latitudes 46° 10′ N. and 47° 00′ N., from about 4 nautical miles offshore to about 70 nautical miles offshore. The positions of soundings in all parts of the area were fixed by the radio-acoustic method. Two shore stations were used, one near Westport, Washington, and one near North Head, Washington. It will be seen that the stations were located near the two inshore corners of the surveyed area; hence, when the ship was at either of the two offshore corners of the area, one of the two hydrophones was receiving sound energy from bombs fired from 75 to 80 nautical miles away. This may be described as good transmission.

The physical conditions in this area are shown in Fig. 2 (*a*), which represents a vertical section at right angles to the shore line from the hydrophone at North Head to 40 nautical miles offshore. The water temperatures are shown in the inset; the temperature gradient is seen to be rather great in the upper layers. The bottom materials probably are not very good reflectors of sound.

(*b*) In the Waters off North Carolina.

During the fall and winter of 1926–27 the *Lydonia* carried on experiments with radio-acoustic position finding off the coast of North Carolina between Capes Fear and Lookout to test the practicability of the method in those waters. The author took part in this work. Sound transmission was so poor that it was decided that the method was not economical in that area. The indications were that even with the hydrophone planted several miles offshore expectation that the hydrophone would receive sufficient energy from bombs fired more than 25 nautical miles away was not justified.

In addition to the poor transmission, the hydrophone circuit was very frequently disturbed by strong strays, especially in the late winter and early spring, believed to be caused by the sounds emitted by fish of the "grunt" family. Had the sound transmission been good enough to make it worth while, these strays probably could have been filtered out. The writer has experimented to some extent with an

electrical filter for similar strays off the Florida coast during the past winter, and the indications were that the filter would remove the strays almost entirely without seriously attenuating the energy from the bombs.

Fig. 2 (*b*) shows the physical conditions in the North Carolina area; it represents a vertical section at right angles to the shore line from the hydrophone at New River Inlet to 40 nautical miles offshore. The vertical scale is twice that in Fig. 2 (*a*). The temperature conditions of the water are shown in the inset; the temperature gradient is seen to be small. The bottom materials in this area are believed to form a surface that is favorable for the efficient reflection of sound energy.

(*c*) In the Waters off Florida.

During the past winter (1927–28) the *Lydonia* has carried on experiments with radio-acoustic position finding off the coast of Florida between St. Augustine and Cape Canaveral. The writer took part in these experiments. Sound transmission was found to be apparently somewhat better than off the North Carolina coast, although Fig. 2 (*c*) shows that the vertical section of the water at right angles to the shore line is not materially different from that in North Carolina, nor are the bottom materials believed to form any better reflecting surface than do those of North Carolina. Very few temperature data had been obtained up to the time of preparation of this dissertation; the inset shows the temperature conditions according to this inadequate data. Surprising as it may seem, the water is considerably colder than that in North Carolina. The conclusions from the Florida work were that with the hydrophone two nautical miles or more offshore, it is safe to expect the hydrophone to receive sound energy from bombs fired within a radius of 30 to 35 miles; expectations of a greater range did not appear to be justified.

DISCUSSION OF RADIO-ACOUSTIC EXPERIENCE.

The writer will not presume to decide why the transmission of sound in radio-acoustic work is good to excellent off the coasts of Washington and Oregon and poor to fair off the coasts of North Carolina and Florida. It will be well to consider what seem to be the probable factors affecting sound

transmission. One of the writer's associates, for whose scientific attainments and judgments he has very great respect, believes that within reasonable limits of depth of water the deciding factor is that of temperature gradient. If the gradient is great from surface to bottom, with the temperature decreasing with depth, the sound energy will be refracted downward and the associate mentioned believes that in such circumstances sound transmission will be poor. The writer agrees that such temperature conditions would be disadvantageous, but does not believe that temperature gradient is the deciding factor.

It is held by some of the writer's associates on the basis of experience that within reasonable limits of other conditions cold water will transmit the sound more effectively than warm water. This belief apparently is supported by the fact that transmission seemed to be better on the Florida coast than on the North Carolina coast, and also by the tests carried out by the *Guide* in Long Island Sound in November, 1923,[1, 13] in which tests the writer took part. Assuming equal temperature gradients the writer confesses himself at a loss to understand why water of low mean effective temperature should transmit sound better than water of higher mean effective temperature. As a matter of fact Aigner [21] has shown that the viscosity absorption loss of sound energy in sea water is decidedly less in warm water than in cold.

If in a given area transmission is better in winter than in summer the writer believes that the better transmission is due to a smaller temperature gradient (the surface temperatures more nearly equaling the bottom temperatures than in summer) rather than to a lower mean effective temperature.

It should be stated that many more tests were made with the hydrophone two miles or more offshore in Florida than in North Carolina, where all such experiments were discouraged by the strays attributed to the "grunts." The author considers it quite possible that if the tests were carried out in North Carolina during a time of year when the "grunts" were not active and with the hydrophone two miles or more offshore, just as good results might be obtained as in Florida.

It is significant that in North Carolina and Florida the hydrophone had to be placed about two miles or more offshore

to get the maximum range. In Florida, with the hydrophone one-half nautical mile offshore the range was about five miles; when it was 1.45 nautical miles offshore its range was 20 to 25 miles; when it was 2.1 nautical miles offshore its range was about 35 miles; when it was 10 nautical miles offshore its range was no greater than at 2.1 miles off. The experience in North Carolina was similar in this respect. On the Washington and Oregon coasts, however, in general no such effect was noted; one of the best stations, that at Port Orford, Oregon, (see account above of 200-mile run) had the hydrophone planted about 200 yards offshore.

Some of the associates of the writer hold that the amount of solid matter in suspension in the water is an important factor in sound transmission, transmission being poor (they state) when there is much suspended matter. The author has no data on the relative amounts of suspended matter in the waters off Washington-Oregon, North Carolina and Florida.

The fact remains that the transmission off either Florida or North Carolina is not nearly so good as off Washington and Oregon. The writer admits that a considerable temperature gradient, with temperature decreasing from surface to bottom, is probably unfavorable for good horizontal sound transmission. He is not ready to admit that sound is transmitted more effectively in cold water than in warm, with equal gradients. Nor is he ready to admit that the amount of suspended solid matter in the water, within reasonable limits, is an important factor in sound transmission. Granting that the surface and bottom in North Carolina and Florida are probably better reflectors than those in Washington and Oregon, nevertheless on the basis of his hypothesis as to the manner of sound transmission in radio-acoustic work, the author believes that the sound transmission is better off the Washington and Oregon coasts principally because the bottom slopes off more rapidly from the shore line to seaward so that the average depth of water between bomb and hydrophone is always considerably greater than is the case off North Carolina and Florida. In this connection the writer will quote from his hypothesis as to the manner of sound transmission as stated earlier in this dissertation. "If the water between bomb and hydrophone is deep, fewer reflections and less loss

of energy by reflection will occur than if the water is shoal, that is, a given quantity of sound energy released by a sound source can be transmitted practically to greater distances in deep water than in shoal water."

The author and his associates are open minded in the matter and will welcome suggestions from physicists and others as to the probably important factors affecting the horizontal transmission of sound through sea water. (See page 791.)

PHENOMENA OBSERVED IN CONNECTION WITH RADIO-ACOUSTIC POSITION FINDING AND ECHO SOUNDING.

Shielding of the Hydrophone.

In the first three seasons (winter of 1924, summer and fall of 1924, winter of 1924–25) of radio-acoustic work in the Coast and Geodetic Survey, the hydrophones were mounted so as to be fully exposed to the water and the hydrophone circuit was at most times continually being disturbed by strays of moderate intensity. The writer took part in all of this work and taxed his ingenuity to the utmost in his efforts to eliminate this trouble, which was so serious that it raised serious doubts as to the practical value of the radio-acoustic method.

These strays, or "parasite noises," received the name of "water noises," because some of the associates of the writer believed that they were caused by the roar of the surf on the beach. The writer never held this opinion, but believed that the strays were due to subsurface water currents flowing over the exposed hydrophone; these currents, in addition to the action of the water itself, perhaps cause sand, bits of shell, etc., to strike the hydrophone. Also, the hydrophone current had been observed to "breathe," i.e., increase and decrease slowly in value, which the writer attributed to the periodic changes in the hydrostatic pressure at the hydrophone caused by the passage of surface waves.

It was suggested by Dr. E. A. Eckhardt that the hydrophone might well be shielded by enclosing it in a perforated metal case. This was tried and effected no appreciable improvement.

In reading "Mechanical Properties of Fluids," by Drysdale and others, the author came upon an account of the work of Brillié, in which the latter had found the acoustic resistance

of certain kinds of wood to be nearly equal to that of sea water. It occurred then to the writer that if the hydrophone be enclosed in a fairly large, watertight wooden case, as for example a keg, filled with sea water, sound would pass through the wood and reach the hydrophone without attenuation, while the hydrophone would be completely shielded from mechanical disturbances. Some preliminary experiments were conducted by the writer, assisted by Almon M. Vincent, Chief Wireless Operator of the *Guide*. These experiments, in which two matched hydrophones were used, one exposed and one sealed in a keg full of sea water, gave very encouraging results. The shielded hydrophone was quite as sensitive to *sound* as the exposed one; the exposed one was subject to strays as usual, while the shielded one was almost entirely free from such disturbances. At the Port Orford station mentioned above in connection with the 200-mile test run of August, 1925, a single hydrophone was used, sealed in the keg used in the preliminary experiments. At Hunter's Cove three hydrophones in parallel were sealed into an oak box made for the purpose. In the box made for the hydrophone at Brookings several one-half-inch holes were bored; it is perhaps significant that the hydrophone circuit at that station was disturbed by strays as usual.

Since that time all the radio-acoustic hydrophones used by the Coast and Geodetic Survey have been sealed into watertight wooden cases filled with sea water, with very beneficial results on the Pacific Coast. On the coast of North Carolina the hydrophone cases did not eliminate the bad strays, because these strays were *sound* and not mere mechanical disturbances.

The writer has made a study of Brillié's original paper.[14] It is shown that where sound passes successively through three media of acoustic resistances n, n_1, n_2, then if

$$r_1 = \frac{n_1}{n} \quad \text{and} \quad r_2 = \frac{n_2}{n_1},$$

$$(1) \quad \frac{\text{Energy transmitted}}{\text{Energy incident}} = \frac{4r_1r_2}{(r_1r_2 + 1)^2} \times \frac{1}{1 - \sin^2 a_1 \dfrac{(r_1^2 - 1)(r_2^2 - 1)}{(r_1r_2 + 1)^2}},$$

where

$$a_1 = 2\pi \frac{l_1}{L_1},$$

l_1 being the thickness of the second medium.

If $n = n_1 = n_2$ as when the first and third media are sea water and the second is a material having the same acoustic resistance as sea water, the expression on the right becomes equal to unity and the sound is transmitted without attenuation.

If a_1 is nearly zero, i.e., if the thickness of the second medium is sufficiently small relative to the wave-length of the sound, then, as Brillié points out, we may set $\sin^2 a_1$ equal to zero, and we have

$$(2) \qquad \frac{\text{Energy transmitted}}{\text{Energy incident}} = \frac{4r_1r_2}{(r_1r_2+1)^2} \frac{4\frac{n_2}{n}}{\left(\frac{n_2}{n}+1\right)^2},$$

which is as though the second medium did not exist, i.e., we need not be so careful to have its acoustic resistance near to that of sea water.

It may be stated as a matter of experience that sound from TNT bombs fired under water passes without appreciable attenuation through wooden cases having wall thickness of from one to two inches of any available hard wood; the wave-length of the sound is not definite but probably ranges from about fifteen feet to greater lengths. On the other hand, Dr. Herbert Grove Dorsey, Senior Electrical Engineer of the Coast and Geodetic Survey, found that wooden planks four inches thick were scarcely penetrable by sound of wave-length about five feet.

As Brillié points out, if the thickness l_1 of the second medium is equal to an exact multiple of half wave-lengths, then $\sin^2 a_1$ will be equal to zero and Eq. (2) will apply. It has occurred to the writer that this principle may serve as a means of shielding ultra-sonic receivers from "parasite noises" or strays, where these are due to mechanical disturbances; the wave-lengths of ultra-sonic energy range from about one-twentieth to one-sixth of a foot, i.e., from a little more than

one-half inch to about two inches. In the *Hydrographic Review*, Vol. IV, No. 2, November, 1927, is given an account of a considerable amount of trouble being experienced in such a receiver due to "parasite noises." The writer would suggest that if it were feasible to shield this receiver by a case of which the wall thickness is very nearly an exact multiple of the wave-length, the "parasite noises," if due to mechanical causes, might be eliminated without appreciable attenuation of the ultra-sonic energy.

RELATIVE ATTENUATION WITH DISTANCE OF SOUNDS OF GREAT AND OF SMALL AMPLITUDES.

Stokes, Rayleigh and Hart have shown [15] that in the transmission of sound energy through air, sounds of great amplitude have a greater relative decrease of intensity with increasing distance from the source than do sounds of small amplitude. Experience with radio-acoustic position finding has given qualitative evidence of the same effect in sea water, as might be expected. For example, if the ship is within ten or fifteen miles of a given hydrophone a no. 8 blasting cap fired in the water near the ship will usually send plenty of energy to that hydrophone to trip the apparatus; apparently a five-inch, cast iron, TNT filled bomb, of the type described earlier in this dissertation will not deliver more than about twice as much power as the blasting cap to the given hydrophone. The indications are that there will certainly be a limit to the range of a given hydrophone that cannot be increased, no matter how large or powerful the source of sound; this is probably because the more powerful the source, the more rapidly does the amplitude of the waves originating from that source decrease with increasing distance from the source.

VARIATION OF SPEED WITH INTENSITY.

Early in 1925, the writer, under the direction of Lieutenant Commander Thomas J. Maher, U. S. Coast and Geodetic Survey, Commanding Officer of the *Guide*, experimented with recording on a chronograph tape the times of explosion of blasting caps fired just beneath the surface of the water and the times of return of the echoes from the bottom, as a means of measuring depth roughly in fairly deep water. In 200 to

400 fathoms of water the method gave rather good results. Several echoes were recorded from each explosion. *The interval between the explosion and the return of the first echo was roughly only about half of the intervals between successive echoes*, presumably because of the great intensity of the wave before the first reflection from the bottom. The intervals between successive echoes apparently were equal and gave the correct depth to a fair approximation.

This recalls the work of Threlfall and Adair.[19] Glazebrook [18] gives so good an account of this work that it seems well to quote him here verbatim.

"Threlfall and Adair published in 1889 their experiments on the speeds of sound-waves from explosions under water in Port Jackson harbour, Australia. Charges of gun cotton were used; the firing was electrical and gave a signal on a chronograph, on which also was recorded the instant when the sound reached an india rubber diaphragm immersed at the far station 150 meters of more distant. The normal speed for feeble sounds in water was calculated to be about 1,500 meters per second; the observed speed of the explosion wave from 9 oz. of gun cotton was 1,732 meters per second and from 64 oz. of gun cotton was 2.013 meters per second."

Reference has already been made to the work of Regnault, which indicated a similar effect in air (p. 20).

APPENDIX. A BRIEF DISCUSSION OF METHODS IN USE IN THE U. S. COAST AND GEODETIC SURVEY FOR THE MEASUREMENTS OF DEPTH OF WATER.

In comparatively rare cases very shoal depths are measured with poles. This method is necessarily limited to water that is not more than about 2 fathoms deep.

Depths of 15 to 20 fathoms and less can be sounded economically by means of the hand lead and line. The ship sounds to as near shore as considerations of safety will permit; the areas nearer shore than this are surveyed by power launches or pulling boats. When the hand lead and line is used by the ship she runs continuously at a speed of about 6 knots. Power launches and pulling boats sounding with hand lead and line operate at somewhat lower speeds. Soundings are taken at intervals of about a minute or less.

"Trolley sounding" is similar to hand lead sounding but can be carried economically to depths of about 30 or 35 fathoms. The lead is dropped from forward and the line becomes vertical with the lead on the bottom to the leadsman stationed aft. As in hand lead work the leadsman reads off the depth from marks on the line. The lead is hauled in ready to drop from forward again by a power reel located forward. As in hand lead sounding the ship runs continuously at a speed of about 6 knots; soundings are taken at intervals of about 1½ minutes.

"Wire soundings" are carried out by means of a heavy lead (in deep water a detachable "shot") lowered by stranded or solid steel piano wire wound on a drum. The wire passes around a carefully calibrated sheave, which measures the number of fathoms of wire run out with considerable precision. The wire is reeled in by power on board ship and by hand on board a small boat. The method is applicable to any depth. The ship or boat must be kept "dead in the water" during a wire sounding in order to keep the wire vertical. Since the development of acoustic sounding methods, wire soundings are used principally as checks on the accuracy of acoustic soundings and pressure tube soundings.

Pressure tube soundings are applicable to depths from about 15 fathoms to about 80 fathoms. The Rude-Fischer tube is used, in which enough water is forced into the tube through a capillary opening in the cap to compress the air in the tube to equilibrium with the hydrostatic pressure outside. The capillary opening becomes water sealed so that neither the air nor the entrapped water can escape. The quantity of water forced in is a measure of the depth to which the tube has been lowered. During pressure tube sounding the ship runs continuously at a speed of about 6 knots and soundings are taken at intervals of about one or two minutes. The wire sounding machine is used in pressure tube sounding, a short length of cotton or manila line is placed between the lead and the end of the wire, and the tube is secured to this line just above the lead. Acoustic sounding with the "fathometer" is more or less superseding pressure tube work.

The "fathometer" equipment, manufactured by the Submarine Signal Corporation, consists of: (1) an electrically

driven oscillator with its diaphragm outside the skin of the ship below the water line, for generating short powerful sound impulses; (2) a microphone mounted in a tank full of water in contact with the inside of the ship's plating below the water line, and connected through a filter and amplifier to a neon tube and head phones, for receiving echoes of the oscillator signals from the ocean bottom; and (3) a device for measuring the time of return of the echo, consisting of a disk rotating at known, uniform speed behind a translucent dial graduated in fathoms, about an axis through its center perpendicular to its plane, and having two radial slits with the neon tube behind one and a fixed white light behind the other. The oscillator is made to sound when the neon tube slit and the white light slit are in line with the zeros of their respective scales on the translucent dial. In depths less than about 150 or 200 fathoms the neon tube flashes when the return echo is received, and since oscillator signals are sounded at intervals of ¼ second the result is a flickering luminous red indicator pointing out the depth of water on the dial. In deep water the disk carrying the slits is made to rotate more slowly, the oscillator signals are made to sound at greater intervals, and it is necessary to note the position of the white slit on the dial when the echo is heard in the phones. With a large oscillator this "white light method" is applicable to the greatest known depths. The "red light method" is not yet used for survey work in depths less than about 15 fathoms.

The "sonic depth finder," according to the experience of the writer, is applicable for survey work in depths from about 80 fathoms to the greatest known depths. The method of producing the sound is exactly that used in the fathometer and the method of receiving the echo is essentially the same. The distinctive feature, developed by the U. S. Navy, is the method of measuring the time of return of the echo. The oscillator signals are sounded at regular, adjustable, measurable intervals. The length of this interval is adjusted until the echo returns at the same instant as the first, second or third succeeding oscillator signal is sounded. The time of return of the echo is then equal to, or a known whole multiple of, the interval between oscillator signals. The sonic depth finder is being superseded on board the ships of the U. S. Coast and Geodetic Survey by the fathometer.

Soundings taken by any method are all reduced to the same stage of the tide, usually mean low water or mean lower low water, and as stated elsewhere in this dissertation echo soundings are reduced to the speed of sound corresponding to the physical conditions of the water where and when the soundings are taken.

In some areas obstructions of small extent are likely to occur, such as pinnacle rocks for example, that are especially dangerous to navigation but are not likely to be discovered by the methods above discussed. In such areas the above methods are supplemented by dragging operations with the wire drag or sweep.[16]

The author wishes to express his appreciation to Commander W. E. Parker, Chief of the Division of Hydrography and Topography of the Coast and Geodetic Survey, and to Lieutenant Commanders Thomas J. Maher and R. F. Luce, and Lieutenant K. T. Adams, Commanding Officers of the Survey Ships *Guide*, *Pioneer* and *Lydonia*, respectively, who as the author's superior officers have afforded him many opportunities to carry on investigations in the subject of this paper. Also, it is a pleasure to express gratitude to Dr. T. Wayland Vaughan for temperature and salinity data furnished by the Scripps Institution of Oceanography for the ocean waters off the coasts of Washington and Oregon. Finally, the author acknowledges gratefully the help given him by Mr. Roswell C. Bolstad and Mr. Harold J. Oliver, Deck Officers in the Coast and Geodetic Survey, who inked and lettered the illustrations.

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AUTOBIOGRAPHY

I, Jerry Hall Service, was born in New Carlisle, Indiana, June 12, 1888,. I received my secondary school education in the public and high schools of New Carlisle and of Mishawaka, Indiana; my undergraduate education at Northwestern University and at Rose Polytechnic Institute, from which I obtained the degree of Bachelor of Science (in Electrical Engineering) in 1912. During the school years 1912-15 I was employed as Engineering Apprentice by the General Electric Company and later as teacher of shop work, physics and mathematics in secondary schools. Was Graduate Assistant in Physics in the Ohio State University, 1915-16, and Assistant in Physics, 1916-17; obtained the degree of Master of Science from the Ohio State University in 1917. During the year 1917-18 I was a Private, 1st class, U. S. Army, and was assigned as Assistant to the late Professor H. C. Lord in the U. S. Army School of Military Aeronautics; beside teaching several subjects in the School of Military Aeronautics and assisting Professor Lord in the work of that school, I taught all the University courses in General Astronomy and in Geodetic Astronomy. I served as Instructor in Physics in the Ohio State University, 1918-19. During the year 1919-20 I served as a sailor before the mast in order to study at first hand the marine applications of physics and astronomy; had a successful year and was certified as Able-Bodied Seaman and as Life Boat Man, and licensed as Third Mate of Ocean Steam Vessels by the U.S. Steamboat Inspection Service. 1920-23 I was employed as Dean of the Trade and Engineering Schools of the Youngstown (Ohio) Institute of Technology. In the fall of 1923 I entered the service of the U. S. Coast and Geodetic Survey as Mate and have advanced to the commission that I now hold, that of Junior Hydrographic and Geodetic Engineer, with the relative rank of Lieutenant (j. g.) in the Navy. I now hold License from the U. S. Steamboat Inspection Service as Chief Mate of Steam Vessels of any tonnage on the waters of any ocean. During the years 1925-27 I carried on graduate study at the U. S. Bureau of Standards and at George Washington University. During all four

quarters of 1927 and the Winter Quarter of 1928 I have maintained registration in the Graduate School of the Ohio State University for off campus research upon the subject of this dissertation, and in fact since January, 1924, I have been carrying on this work under the supervision of Professor A. D. Cole, with the express purpose of making it the subject of my doctorate dissertation. During the Spring Quarter of 1928 I have been in residence, carrying graduate courses in Physics and Mathematics.